

BATH AND METHOD FOR HIGH RATE COPPER DEPOSITION

FIELD OF THE INVENTION

The invention is in the field of electroplating copper on a microelectronic
5 workpiece using a plating bath. More particularly, the invention relates to electroplating
copper on a microelectronic workpiece in a plating bath wherein the copper is deposited
at a high rate in a through-mask plating application.

BACKGROUND OF THE INVENTION

Copper electroplating uses the process of electrolysis to deposit copper atoms on
10 an object acting as the cathode, or negative electrode. Applications of electroplating of
copper on microelectronic substrates in a plating bath can be divided into several
categories, such as interconnect plating applications, micro-electro-mechanical systems
(MEMS) plating applications, and bump plating applications. These pattern plating
applications can be mainly divided into through-mask plating applications (photoresist
15 pattern plating applications such as bump applications, MEMS applications, and
redistribution applications) and through-hole and blind-hole plating applications (pattern
plating applications without photoresist, for example, interconnect applications).

In bump plating applications, the most commonly used solders for flip-chip
applications are eutectic tin-lead (63/37), eutectic tin-silver (96.5/3.5), eutectic tin-copper
20 (99.3/0.7), and near-eutectic tin-silver-copper (Sn/3.5-4.5Ag/0.3-0.9Cu) alloys. In most
cases, a thick copper layer, a so-called copper mini-bump, is deposited to provide a
solder-wettable surface on the top of an unwettable diffusion barrier as well as to form a
bonding layer through the reaction with the active element (tin) of the solder. Tin-copper
and tin-silver intermetallic compounds are formed during the reflow process.
25 Electrodeposition is the easiest and cheapest way to deposit a thick copper layer. To date,

a copper deposition rate of 0.4-1.0 μm per minute is generally achievable for through-mask plating applications with commercial copper baths developed for interconnect (such as via, trench, and dual damascene) plating applications. One of the shortcomings of this commercial technology is that a copper deposition rate of 0.4-1.0 μm per minute is undesirably slow, not only for bumping applications, but for other through-mask plating applications requiring relatively thick deposits, e.g., microns thick. These slow deposition rates increase the process time required to deposit thick features in through-mask applications. Accordingly, microelectronic device manufacturers must bear the added cost and reduced productivity resulting from such long process times.

Accordingly, the purpose of the present invention is to provide a bath and process that achieves a high rate of copper deposition in through-mask plating applications (a deposition rate of about 2-6 $\mu\text{m}/\text{min}$ or faster, e.g., 4 $\mu\text{m}/\text{min}$ or faster) and produces features with desirable morphology, such as a smooth surface. With these faster deposition rates, process times are reduced and microelectronic manufacturers will enjoy the economic benefit of reduced process times and higher through-put.

SUMMARY OF THE INVENTION

The baths and processes of the present invention fulfill the need of microelectronic manufacturers to deposit copper at rates of at least 2 $\mu\text{m}/\text{min}$ and produce deposits having other desired characteristics.

Baths of the present invention are useful for the high rate electroplating of copper in a through-mask plating application and can achieve (a) a copper deposition rate of at least 2 $\mu\text{m}/\text{min}$, e.g., 4 $\mu\text{m}/\text{min}$ or faster; (b) a smooth surface morphology ($R_a < 30 \text{ nm}$) for the deposited feature; (c) a flat surface (good conformality with photoresist or other dielectric); (d) no dewetting, doming or skewing of the deposited feature; (e) no visible delamination of the deposited feature from the substrate and an adequate adhesion; (f) low dependency of morphology and flatness on feature shape, size, and open area; and (g) a thickness variation of less than 10% (3-sigma).

One embodiment of a plating bath for electroplating copper on a microelectronic workpiece in a through-mask plating application at a rate of at least 2 $\mu\text{m}/\text{min}$ where the bath includes: (a) 50-85 g/L of Cu^{2+} ; (b) 50-100 g/L of H_2SO_4 ; (c) 30-150 ppm of Cl^- ; (d) a brightener; (e) a wetting agent; and (f) optionally a leveler; and (g) the balance is water.

The baths of the present invention are formulated to fully wet all the features on a workpiece, particularly the surface to be electroplated without having a substantial adverse effect on the ability of the brightener to reduce the size of the metal grains and make the surface of the deposit brighter. The bath wets all features on the workpiece so that bubble trapping, pore formation, and/or dendritic growth is minimized. The baths have a low surface tension such that doming and skewing of the deposited copper is minimized. The baths are formulated so that the wetting agent does not have a substantial suppressing effect on the deposition of copper from the bath and does not react and absorb unevenly so as to result in crater-type defect formation within the deposited feature.

Another embodiment of the invention is a process for electroplating copper on a microelectronic workpiece in a through-mask plating application at a rate of at least 2 $\mu\text{m}/\text{min}$ where the process includes the steps of: (a) providing the plating bath described above; (b) providing a microelectronic workpiece which has one or more through-mask openings having a conductive layer at the bottom of the openings; (c) contacting the conductive layer at the bottom of the openings with the plating bath; and (d) providing electroplating power between the conductive layer and an anode disposed in electrical contact with the bath, whereby copper is deposited onto the conductive layer at a rate of at least 2 $\mu\text{m}/\text{min}$.

Another embodiment of the invention is a process for forming solder bumps on a microelectronic workpiece where the process includes the steps of: a) providing a workpiece including a silicon wafer, one or more chip pads, and a passivation layer; (b) applying over the chip pads and the passivation layer a barrier layer and a conductive layer; (c) applying over the conductive layer a photoresist layer and then removing portions of the photoresist layer to create openings in the photoresist layer thereby exposing portions of the conductive layer at the bottom of the openings in the photoresist layer; (d) providing an electroplating bath described above; (e) contacting the conductive layer at the bottom of the openings with the electroplating bath; (f) providing electroplating power between the conductive layer and an anode disposed in electrical contact with the bath, whereby copper is deposited over the conductive layer at a rate of at least 2 $\mu\text{m}/\text{min}$; (g) applying a solder layer over the deposited copper; (h) removing the photoresist layer and thereafter etching away the exposed portions of the barrier layer and

the conductive layer, thereby leaving the portions of the barrier layer and the conductive layer that are situated under the deposited copper feature; and (i) reflowing the solder layer.

Another embodiment of the invention is a process for forming copper features on a microelectronic workpiece where the process includes the steps of: (a) providing a workpiece including a silicon wafer, one or more connectors, and a passivation layer; (b) applying over the connectors and the passivation layer a barrier layer and a conductive layer; (c) applying over the conductive layer a photoresist layer and then removing portions of the photoresist layer to create openings in the photoresist layer thereby exposing portions of the conductive layer at the bottom of the openings in the photoresist layer; (d) providing a plating bath described above; (e) contacting the conductive layer at the bottom of the openings with the plating bath; (f) providing electroplating power between the conductive layer and an anode disposed in electrical contact with the bath, whereby a copper feature is deposited over said conductive layer at a rate of at least 2 $\mu\text{m}/\text{min}$; and (g) removing the photoresist layer and thereafter etching away the exposed portions of the barrier layer and the conductive layer.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and many of the attendant advantages of this invention will become more readily appreciated as the same become better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings, wherein:

FIGURES 1-6 are schematic representations of the steps in a process for through-mask pattern plating in bumping applications employing the high rate copper electroplating process of the present invention;

FIGURES 7-12 are schematic representations of the steps in a process for other types of through-mask pattern plating employing the high rate copper electroplating process, such as for MEMS applications and redistribution applications;

FIGURES 13-15 illustrate bubble trapping, pore formation, or dendritic growth that result when an insufficient amount of wetting agent or a poorly performing wetting agent is employed to deposit copper at a rate greater than about 2 $\mu\text{m}/\text{min}$ in a through-mask plating application;

FIGURES 16 and 17 illustrate doming of copper features resulting when the surface tension of the plating bath used to electroplate copper features at a rate greater than about 2 $\mu\text{m}/\text{min}$ in a through-mask plating application is too high;

FIGURES 18 and 19 illustrate features having uneven surfaces (e.g., non-conformal growth) resulting when a wetting agent is used that has an undesirable suppressing effect on the deposition;

FIGURES 20 and 21 illustrate features deposited in a through-mask plating application having surfaces that are not smooth resulting when the wetting agent is not compatible with the brightener;

FIGURES 22 and 23 illustrate features deposited in a through-mask plating applications where the wetting agent reacts unevenly and/or absorbs unevenly to the feature;

FIGURE 24 is a schematic representation of a tool for electroplating a metal onto a microelectronic workpiece in accordance with the present invention; and

FIGURE 25 is a schematic representation of a tool for forming solder bumps on a microelectronic workpiece employing the high rate copper deposition of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

As used throughout the specification, the following abbreviations have the following meanings, unless the context clearly indicates otherwise: nm = nanometers, mm = millimeters, μm = microns, $\mu\text{m}/\text{min}$ = microns per minute, g/L = grams per liter, ml/L = milliliters per liter, mA/cm² = milliamperes per square centimeter, and ppm = parts per million. All percentages and ratios are by weight unless otherwise indicated. All ranges are inclusive and combinable.

As used throughout the specification, the term "plating" refers to electrolytic deposition, i.e., electroplating, unless the context clearly indicates otherwise. The term "feature" refers to a structure on a substrate. The term "through-mask plating" refers to plating through an opening in a dielectric film, such as a photoresist. The term "through-hole and blind hole plating" refers to plating through an opening in a material, which is not a photoresist. The term "brightener" refers to an organic compound that reduces the size of the grains and thus makes the surface of the deposit brighter. The term "wetting agent" refers to an organic compound that reduces the surface tension of the bath and

prevents pores or pits in the deposit. The term "leveler" refers to an organic compound that is used to improve microthrowing power resulting in deposits with a flat surface. The term "water" refers to deionized water.

5 The components of plating baths of the present invention are now described in more detail below. The following description is intended to illustrate, not limit, the present invention.

BRIGHTENER

A brightener is added to the electroplating baths of the present invention. A wide variety of known brighteners may be employed. Typical brighteners are described in
10 published U.S. Patent Application No. 20020043468, which is incorporated herein by reference. They contain one or more sulfur atoms, no nitrogen atoms, and have a molecular weight of about 1000 or less. Brightener compounds that have sulfide and/or sulfonic acid groups are useful, particularly compounds that comprise a group of the formula $R'-S-R-SO_3X$, where R is an optionally substituted alkyl (which include
15 cycloalkyl), optionally substituted heteroalkyl, optionally substituted aryl group, or optionally, substituted heteroalicyclic; X is a counter ion such as sodium or potassium; and R' is hydrogen or a chemical bond (i.e., $-S-R-SO_3X$ or substituent of a larger compound). Typically, alkyl groups will have from one to about 16 carbons, more typically one to about 8 or 12 carbons. Heteroalkyl groups will have one or more hetero
20 (N, O, or S) atoms in the chain, and preferably have from 1 to about 16 carbons, more typically 1 to about 8 or 12 carbons. Carbocyclic aryl groups are typical aryl groups, such as phenyl and naphthyl. Heteroaromatic groups also will be suitable aryl groups, and typically contain 1 to about 3 N, O, or S atoms and 1-3 separate or fused rings and include, e.g., coumarinyl, quinolinyl, pyridyl, pyrazinyl, pyrimidyl, furyl, pyrrolyl,
25 thienyl, thiazolyl, oxazolyl, oxidizolyl, triazole, imidazolyl, indolyl, benzofuranyl, benzothiazol, and the like. Heteroalicyclic groups typically will have 1 to 3 N, O, or S atoms and from 1 to 3 separate or fused rings and include, e.g., tetrahydrofuranyl, thienyl, tetrahydropyranyl, piperdinyl, morpholino, pyrrolindinyl, and the like. Substituents of substituted alkyl, heteroalkyl, aryl, or heteroalicyclic groups include, e.g., C_1-C_8 alkoxy;
30 C_1-C_8 alkyl, halogen, particularly F, Cl, and Br; cyano; nitro; and the like.

Some specific useful brighteners include, e.g., N,N-dimethyl-dithiocarbamic acid-(3-sulfopropyl)ester, 3-mercapto-propylsulfonic acid-(3-sulfopropyl)ester, 3-mercapto-

propylsulfonic acid (sodium salt), carbonic acid-dithio-O-ethylester-S-ester with 3-mercapto-1-propane sulfonic acid (potassium salt), bisulfopropyl disulfide, 3-(benzthiazolyl-S-thio)propyl sulfonic acid (sodium salt), pyridinium propyl sulfobetaine, 1-sodium-3-mercaptopropane-1-sulfonate, and combinations of the above.

5 A particular brightener is sold under the trademark Copper Gleam ST-901 or Intervia 8540 Additive and is available from Shipley Company, of Marlborough, Massachusetts 01752. According to its Material Safety Data Sheet, the composition of Copper Gleam ST-901 Additive is as follows: water 95.00-99.00%, sulfuric acid < 1.00%, and copper sulfate < 1.00%.

10 WETTING AGENT (SURFACTANT)

 A wetting agent (surfactant) is added to the electroplating baths of the present invention. A variety of known wetting agents may be employed. Typical surfactants are described in published U.S. Patent Application No. 20020043468, which is incorporated herein by reference. Particularly useful surfactants for plating compositions of the
15 invention are commercially available polyethylene glycol copolymers. Such polymers are available from BASF Corporation, in Mount Olive, New Jersey, 07828, under the trademark PLURONIC.

 A particular wetting agent, which is mixed with a leveler, is sold under the trademark Copper Gleam ST-901 or Intervia 8540 Carrier, which is also available from
20 Shipley Company. According to its Material Safety Data Sheet, the composition of Copper Gleam ST-901 Carrier is as follows: water 85.00-95.00%, sulfuric acid < 1.00%, copper sulfate < 1.00%, and polyether polyol 1.00-10.00%.

CHLORIDE

 Chloride (Cl^-) is provided in the bath by adding HCl to the electroplating baths
25 of the present invention.

LEVELER

 A leveler may optionally be added to the present electroplating baths. A wide variety of known levelers may be employed. Typical levelers are described in published U.S. Patent Application No. 20020043468, which is incorporated herein by reference. In
30 general, useful leveling agents include those that contain a substituted amino group such as compounds having R-N-R' , where each R and R' is independently a substituted or unsubstituted alkyl group or a substituted or unsubstituted aryl group. Typically, the

alkyl groups have from 1 to 6 carbon atoms, more typically from 1 to 4 carbon atoms. Suitable aryl groups include substituted or unsubstituted phenyl or naphthyl. The substituents of the substituted alkyl and aryl groups may be, for example, alkyl, halo, and alkoxy.

5 More specifically, useful leveling agents include, but are not limited to, 1-(2-hydroxyethyl)-2-imidazolidinethione, 4-mercaptopyridine, 2-mercaptothiazoline, ethylene thiourea, thiourea, alkylated polyalkyleneimine, N-heteroaromatic rings containing polymers, quaternized, acrylic, polymeric amines, polyvinyl carbamates, pyrrolidone, and imidazole.

10 HIGH RATE ELECTROPLATING BATHS

 An exemplary bath for electroplating copper on a microelectronic workpiece wherein the copper is deposited at a high rate of deposition (a deposition rate of 2-6 $\mu\text{m}/\text{min}$ or greater) in a through-mask application is set forth in the following Table 1.

TABLE 1

Component	Concentration
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	200-340 g/L Preferred 240-280 g/L
Cu^{2+} (from $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$)	50-85 g/L Preferred 60-70 g/L
H_2SO_4	50-100 g/L Preferred 75-85 g/L
Cl^- (from HCl)	30-150 ppm Preferred 60-110 ppm
Brightener	0.1-10 ml/L Preferred 2-8 ml/L
Wetting agent	1-30 ml/L Preferred 2-10 ml/L
Water	Balance
Bath temperature	25-35°C

Another exemplary electroplating bath for electroplating copper on a microelectronic workpiece wherein copper is deposited at a high rate of deposition (i.e., about 2-6 $\mu\text{m}/\text{min}$) is shown in the following Table 2.

TABLE 2

Component	Concentration
$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	200-340 g/L Preferred 240-280 g/L
Cu^{2+} (from $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$)	50-85 g/L Preferred 60-70 g/L
H_2SO_4	50-100 g/L Preferred 75-85 g/L
Cl^- (from HCl)	30-150 ppm Preferred 60-110 ppm
Brightener	0.1-10 ml/L Preferred 2-8 ml/L
Wetting agent	1-30 ml/L Preferred 2-10 ml/L
Leveler	0.1-10 ml/L Preferred 1-6 ml/L
Water	Balance
Bath temperature	25-35°C

Baths useful for through-mask plating in accordance with the present invention have copper contents, which are generally higher than the copper content of commercial copper electroplating baths used for interconnect plating applications. In addition, baths of the present invention have acid contents that are lower than the acid contents of many commercial copper electroplating baths used for interconnect plating applications.

As described above, copper electroplating baths useful for through-mask applications are able to fully wet the surface onto which copper is to be plated. The ability of the baths to fully wet the surface is achieved by selecting a wetting agent that provides the necessary wetting properties to the bath without the undesirable results discussed above. The wetting agent decreases the surface tension of the solution so that it is able to fully wet the surface to be plated. A sufficient amount of the wetting agent must be used so that good wetting of the surface to be plated is achieved. When an

insufficient amount of wetting agent is employed, or when the wetting agent is not effective, bubble trapping, pore formation, or dendritic growth is observed as illustrated in FIGURES 13-14. The wetting agent desirably reduces the surface tension of the solution sufficiently so that the effect of the flow direction of the plating solution does not substantially affect the shape of the deposited features. When the surface tension of the solution is too high, doming or skewing of the deposited feature is typically observed. Examples of undesirable doming or skewing of the deposited feature are illustrated in FIGURES 16 and 17.

Suitable wetting agents do not suppress the deposition irregularly so as to result in non-conformal growth. Examples of undesirable non-conformal growth are illustrated in FIGURES 18 and 19. The wetting agent needs to be compatible with the brightener so that the wetting agent does not impede the ability of the brightener to reduce the grain size and produce smooth bright surfaces. FIGURES 20 and 21 illustrate results achieved when a wetting agent that is not compatible with a brightener is employed.

Wetting agents useful in the present invention must also react evenly and absorb evenly on the features to be plated. If the wetting agent is unable to do so, formation of craters or pitting in the deposited surface results. Examples of the formation of such craters are illustrated in FIGURES 22 and 23.

An exemplary bath exhibits a droplet contact angle with copper or a photoresist of less than about 20 degrees. Contact angle is a quantitative measure of the wetting of a solid by a liquid. It is defined geometrically as the angle formed by a liquid at the three-phase boundary where a liquid, gas, and solid intersect. Baths useful in accordance with the present invention have surface tensions ranging from about 45-60 dyne/cm at 20°C and about 35-50 dyne/cm at 30°C. The surface tension of the bath may fall outside these ranges, provided satisfactory wetting of the surface onto which copper is to be plated is achieved.

An exemplary bath of Table 1 contains 65 g/L Cu^{2+} , 80 g/L H_2SO_4 , 70 ppm Cl^- , 3 ml/L of a brightener available from Shipley-Ronal Company under the designation B-2001 and 2 ml/L of a surfactant previously available from Minnesota Mining and Manufacturing Company under the product designation FC99. Another exemplary bath

substitutes a brightener available from Enthone Company under the designation CuBath SC-MD in an amount of 6.4 ml/L.

Exemplary baths of Table 2 include 65 g/L Cu^{2+} , 80 g/L H_2SO_4 , 100 ppm Cl^- , 5 ml/L of the brightener available from Shipley Ronal under the designation Intervia 8540-A and 5 ml/L of a mixture of a leveler and a surfactant available from Shipley-Ronal Company under the designation Intervia 8540-C. Another exemplary bath of Table 2 replaces the brightener in the bath described above with 6.4 ml/L of a brightener available from Enthone under the designation CuBath SC-MD, and employs 1.6 ml/L of a leveler available from Enthone under the designation CuBath SC-LO and 2 ml/L of a surfactant available from Minnesota Mining and Manufacturing Company under the designation FC99 in place of the Intervia 8540-C combination of a leveler and surfactant. A third exemplary bath of Table 2 includes 85 g/L Cu^{2+} , 60 g/L H_2SO_4 , 100 ppm Cl^- , 5 ml/L of a brightener available from Shipley-Ronal under the designation Intervia 8540-A, and 10 ml/L of a combination of a leveler and a surfactant available from Shipley-Ronal under the designation Intervia 8540-C.

THE HIGH RATE ELECTROPLATING PROCESSES

Another embodiment of the invention is a process of using a plating bath (as described above) for electroplating copper on a microelectronic workpiece, such as a silicon wafer wherein the copper is deposited at a high rate of deposition (a deposition rate of 2-6 $\mu\text{m}/\text{min}$ or greater, e.g., 4 $\mu\text{m}/\text{min}$ or greater).

The processes of the present invention may suitably be carried out in a commercially available apparatus, which are arranged and have controllers that are modified to be programmed to carry out an electroplating process in accordance with the present invention. One suitable tool system for implementing the present invention is the PARAGON™ model plating tool, an APx™, or an EQUINOX® model plating tool available from Semitool, Inc., of Kalispell, Montana. In addition to the foregoing tools, systems suitable for electroplating metals offered by other manufacturers are also useful.

In general, the tool system includes a reactor, a bath supply source, an electrode, a power supply, and a controller. The reactor receives the workpiece and exposes its microelectronic surface to a plating bath of the present invention. The bath supply source provides the plating bath to the reactor. The electrode, which functions as the anode

during the plating process, is in electrical contact with the plating bath. The power supply supplies electrical power between the microelectronic surface of the workpiece, which functions as the cathode during the plating process, and the anode to electrolytically deposit a metal layer on the microelectronic surface of the workpiece.

5 FIGURE 24 is a schematic representation of a suitable tool system 300 for electroplating a metal onto the microelectronic workpiece, such as a semiconductor wafer. The tool system 300 may include a plurality of workstations for carrying out prewet, spin/rinse dry and plating steps. The particular arrangement of the various workstations can vary; however, an exemplary layout is illustrated in FIGURE 24. In FIGURE 24,
10 workstations 310 and 320 are copper electroplating reactors. Workstations 330, 340, 350, 380, 390, and 400 are solder deposition reactors. Workstations 360 and 370 are spin/rinse dry chambers, which can be used for spin/rinse dry as well as prewetting. In this configuration, the workpieces will pass through a spin/rinse dry chamber followed by a copper electroplating reactor followed by a spin/rinse dry chamber, a solder deposition
15 reactor, and a final spin/rinse dry chamber. In an alternative embodiment not involving the deposition of solder, an exemplary tool 410, illustrated in FIGURE 25, includes spin/rinse dry chambers at workstations 420, 430, 470, and 480. The balance of the workstations then comprise copper electroplating reactors at workstations 440, 450, 460, 490, 500, and 510. In this tool, the microelectronic workpieces travel from a spin/rinse
20 dry chamber to a copper electroplating chamber followed by an additional spin/rinse dry chamber.

An exemplary power supply 380 for the process provides up to 10 volts at an average current of 30 amps and a peak current of 60 amps. The power supply requirements will change depending on the size of the area to be electroplated on the
25 workpiece. The current density may be 100-300 mA/cm². A particularly useful current density is 150-220 mA/cm². The waveform may be a pulse with a 10-50% duty cycle at 50-1000 Hz, as well as a DC. A particularly useful waveform is a DC and a pulse with a 50% duty cycle at 100 Hz. The power supply and other components of the tool are controlled by controller 400.

30 An exemplary mode of electroplating is to rotate the workpiece in a plating chamber at a speed of 20-200 revolutions per minute with the plating bath flowing against the workpiece at a flow rate of 1-10 gallons per minute. For a 150~200 mm-diameter

wafer, the most preferred rotation speed is 20-60 revolutions per minute. For a 150~200-mm diameter wafer, the most preferred flow rate is 4-6 gallons per minute

PROCESS FOR BUMPING APPLICATIONS

FIGURES 1-6 illustrate a process for forming bumps using the high rate copper electroplating process of the present invention. FIGURE 1 shows workpiece 20 which includes silicon wafer 26, chip pad 24, and passivation layer 22, for example, made of silicon dioxide. The chip pads are typically made of aluminum or copper. Pad 24 is one of many pads where the solder bumps will be located. The size of the pads range from 10 to 200 μm in diameter.

The next steps in the process flow are a sputter etching step and then the steps of sputtering on two thin metal films. In order to remove the native oxide layer on chip pads 24, sputter etching is used to remove the oxide layer before sputtering on first thin metal film 28 and thereafter second thin metal film 30 on the workpiece as shown in FIGURE 2. These thin metal films are referred to as under bump metallurgy (UBM). The first metal film 28 is typically made of a diffusion barrier material, such as Ti, TiW, Cr, or TiN. These materials provide a diffusion barrier and possess good adhesion to passivation layer 22. The second thin metal film 30 is composed of a conductive material, such as copper, which is sputtered on and which functions as a seed layer for the later electroplating step.

In FIGURE 3, a photoresist layer 32 has been applied to the workpiece and then, portions of the photoresist have been removed to create openings 33. The openings in the photoresist create a pattern or mask where copper electroplating will later occur. While the process is described with reference to a photoresist, through-mask plating can also occur through dielectric materials that are not photoresists.

In FIGURE 4, copper layer 34 has been electroplated on top of conductive layer 30 within opening 33 by employing the high rate electroplating process described above. This copper layer 34 is frequently referred to as a stud. Copper layer 34 is then covered by solder layer 36, which is also deposited by electroplating.

In FIGURE 5, the photoresist has been removed using chemical strippers and thereafter the exposed portions of metal films 28 and 30 have been etched away, thereby leaving behind the portions of metal films 28 and 30 that are situated under copper layer 34.

Finally, solder layer 36 is heated and reflowed. The result is reflowed solder bump 36' shown in FIGURE 6 wherein solder bump 36' has a spherical shape. During the reflow process, intermetallic compounds are formed in the solder in zone 38 at the boundary of solder bump 36' and copper layer 34.

5 PROCESS FOR OTHER THROUGH-MASK PATTERN PLATING APPLICATIONS

FIGURES 7-12 illustrate a typical process for other types of through-mask pattern plating employing the high rate copper electroplating process, such as for MEMS applications and redistribution applications. In FIGURE 7, workpiece 40 includes silicon wafer 42, connector 44, and passivation layer 46 which, for example, may be made of silicon dioxide. In this type of application, the connectors are where the features will be located. The size of the connectors range from sub-micron to several hundred microns. The other areas of the wafer are generally covered with the passivation layer.

The next steps in the process are a sputter etching step and then the steps of sputtering on two thin metal films. In order to remove the native oxide layer on connectors 44, sputter etching is used to remove the oxide layer before sputtering on first thin metal film 48 and thereafter second thin metal film 50 on the workpiece as shown in FIGURE 8. Thin metal film 48 is made of a barrier layer material, such as Ti, TiW, TiN, or Cr, which form a good diffusion barrier while at the same time having good adhesion to passivation layer 22. The second thin metal film 50 is made of a conductive material, such as copper, and it is sputtered on to form a seed layer for the later electroplating.

In FIGURE 9, a masking layer such as a photoresist layer 52 has been laid down and then, portions of the photoresist are removed to create openings, such as opening 43. The openings in the photoresist create a pattern or mask where copper electroplating will later occur.

25 In FIGURE 10, copper feature 54 has been electroplated on top of copper seed layer 50 within opening 43 by employing the high rate electroplating process described above. In FIGURE 11, the photoresist has been removed using chemical strippers.

In FIGURE 12, the exposed portions of metal films 48 and 50 have been etched away, thereby leaving the portions of metal films 48 and 50 that are situated under copper feature 54.

Each of the processes described above deposit copper at a rate of at least 2 $\mu\text{m}/\text{min}$, preferably at least 4 $\mu\text{m}/\text{min}$, in through-mask applications. The processes

produce deposited features which have a smooth surface morphology wherein R_a is less than 30 nm and R_p is less than 50 nm. The surfaces of the deposited features are flat with no significant doming or skewing. No visible delamination is observed, scotch tape adhesion test is passed, and the processes exhibit a low dependency of morphology and flatness on feature shape, size, and open area. In addition, the processes provide features wherein thickness variations are less than 10% (3-sigma).

While the preferred embodiment of the invention has been illustrated and described, it will be appreciated that various changes can be made therein without departing from the spirit and scope of the invention.